Chapter One: Hyperspectral imaging in Long Valley Caldera: remote fault and fracture mapping

1.0 Introduction

Long Valley is one of the better-studied calderas in the world, and is one of three active calderas in the contiguous United States. Geological field mapping has been ongoing in the caldera since the 1940s (Chelikowsky, 1940; Gilbert, 1941), while seminal work identifying and characterizing the caldera began in the 1960's (Gilbert, 1968; Smith and Bailey, 1966; Rinehart and Ross, 1964). Suites of increasingly sophisticated geophysical and geochemical studies performed there since the late 1970's have revealed a restless and dynamic volcanic system. The May 1980 south moat earthquake swarm ushered in the current period of unrest and paved the way for even more extensive monitoring and study efforts. The years of study have elucidated much about the structure, tectonics, volcanogenesis, and hydrothermal system of Long Valley. However, there still remain ambiguities regarding caldera structure, tectonics and formational processes. In 1966, Smith and Bailey said that the caldera, "owes its existence to the fault systems of the Sierra Nevada escarpment, upon which it is superimposed". But how much do the Sierra and other regional fault systems impart to the Long Valley region? How much does regional stress guide caldera tectonics versus local volcanic perturbations? Recent work by Prejean (2001) has gone a long way in isolating caldera responses to regional stress. Her work models recent seismicity measured in the Long Valley area as tectonic in origin, rather than volcanogenic. Improved seismic-based maps from her study show new faults in the southern moat, which have already enriched current tectonic and formation models for the caldera.

Prejean's success clearly illustrates that in order to model the tectonics of this caldera as closely as possible, we must amass as many pieces of the structural puzzle as is feasible. We must have the most comprehensive fault and fracture map available. This sentiment was made by Suemnicht and Varga (1988), whose Discovery Fault Zone augmented our understanding of caldera strain accommodation considerably. Models will be more capable of capturing real-world deformation, as a higher resolution of input (eg. comprehensive fault and fracture maps) is introduced to the model system. Are there other fault systems left unrecognized and unmapped?

Hyperspectral imaging is an efficient, synoptic, and dependable way to map faults and fractures in volcanic systems. Hyperspectral remote sensing measures surface material radiance in such a way as to provide continuous spectral maps that not only discriminate but also identify materials such as rocks, minerals, and vegetation. In Long Valley, and other volcanic regions in general, surface hydrothermal alteration is a guide to hydrothermal temperatures and chemistries. More importantly, the spatial distribution of these hydrothermal minerals serve as guides to zones of discharge (both fluid and gas). Invariably, these discharge zones are the faults and fractures that govern caldera permeability and which reflect both local and regional tectonics.

The following study presents caldera-wide maps of faults and fractures, determined from mapping linear zones of hydrothermal mineral distributions. The most helpful mineralization is the argillic phase montmorillinite, kaolinite, alunite assemblage and the amorphous silica/travertine assemblage. Comparing hyperspectrally-mapped faults with previously mapped faults provides several important results. A set of new, previously unrecognized faults are mapped, which meld well with recent tectonic models and suggest new components to these same models. Degree of alteration on these faults is used as a proxy for longevity. The coincidence of previously mapped faults with those identified via hyperspectral imaging is examined closely, because a secondary goal of this study is to evaluate hyperspectral technology abilities for geothermal prospecting and volcano characterization and monitoring. We wanted to ascertain how much of a volcanic system's dynamics and character could be ascertained with only cursory field data and a hyperspectral dataset. Long Valley is unique in having such long-term study and monitoring associated with it, and was thus the perfect locale to test hyperspectral identification of faults and fractures. Such technology may prove invaluable for future exploration or volcanic characterization missions in countries and/or terrains having more difficult access.

2.0 Background

2.1 Regional and local geology

2.1.1 Volcanism in Long Valley

The east-west elongate (32 km x 17 km) Long Valley caldera lies at the base of the Sierra Nevada escarpment, a fault zone which has experienced from 1480-2150m of normal movement over the past ten million years (Huber, 1981; Unruh, 1991; Wakabayashi and Sawyer, 2001). The interplay of extensional Basin and Range tectonics, right lateral shear, and subsequent magma pooling and upward migration, has produced the complex structural system we see today in the eastern Sierra. This system undoubtedly served as the framework for the massive silicic eruption of Long Valley caldera at 760ka (Bailey et al., 1976), though magma generation and caldera formational processes are less well known.

Initial volcanic activity in this region predates caldera formation by almost 2.5 million years. The more mafic Tertiary volcanics east of Long Valley range in age from 3.2-2.6 Ma, and may be part of the initial volcanic cycle at these latitudes that later birthed Long Valley caldera (Bailey et al., 1976). More recent (1.96 Ma) Glass Mountain volcanics lie on the northwest rim of the caldera and probably share the Long Valley magmatic source. The Pleistocene eruption of Long Valley produced ~ 600km^3 of ash and lava that spread great distances (see inset of Figure 1-1). The bulk of the ash and lava was deposited and welded into the Bishop Tuff formation, which locally reaches a thickness of a kilometer or more (see Figure 1 for locations of both the Glass Mountain eruptives and the Bishop Tuff).

After the caldera-forming eruption, several intra-caldera eruptions plagued the newly formed Long Valley. These include the aphyric to sparsely porphyritic rhyolites (751-652ka) of the central resurgent dome and subsequent moat rhyolites, which erupted in a clock-wise pattern around the caldera beginning in the north at approximately 500ka. The northern rhyolites are quite silica-poor, as are the southeastern moat rhyolites, including the Hot Creek flow. These southeastern moat rhyolites erupted at approximately 300ka. Western moat rhyolites, including those comprising Mammoth Knolls and Dry Creek Dome, date to approximately 100ka and are much higher in Si-content than the previous moat rhyolites. All of these flows have been uplifted over the millennia from upward magma migration at depth. Dome reinflation resumed in 1980, with recorded uplift rates of 2-3 cm/yr (Savage et al., 1987; Langbein et al., 1993). Current rates are much less. Other flows include the young (40ka-0.6ka) north-south trending Mono- Inyo volcanic chains that lie in the western caldera. The northern Mono domes are predominately glassy, high silica rhyolites, while the southern Inyo domes and craters are lower in silica, including the rhyodacitic stratovolcano Mammoth Mt., which is the southernmost volcanic center of the chain and is composed of domes and flows dating from 200ka to 35ka.

Mammoth has become increasingly active over the past 10-15 years. Fumaroles de-gas on both the northern and southern flanks, altering the ground to some of the highest concentrations of high temperature mineralization found in the caldera. In addition, earthquakes frequently occur beneath the edifice, including a small magnitude swarm in 1989 that probably accompanied a dike intrusion at depth (Hill et al., 1990). The total moment magnitude of all the events that took place over a six-month period didn't exceed M4.0, but recent seismic relocation work by Prejean, (2001) supports the intrusion hypothesis and indicates that magma movement began at initial depths of 7-9 km and rose to within approximately 1 km of the surface over the six month time period. Later, shallower events were concentrated on two half-ring structures that may represent stress concentrations above an intruded pocket of magma (Nettles and Ekstrom, 1998). The seismicity was accompanied by degassing of magmatic CO_2 from the shallow magmatic intrusions. This degassing continues to the present day and averages approximately 300 tons/day of CO_2 (Sorey et al., 1999). The CO_2 flux has resulted in the death of hundreds of hectares of dead trees, countless dead animals, and one dead human.

Recent volcanic activity in the Mono-Inyo chain occurred ~600 years ago with phreatic explosion pits on the north flank of Mammoth Mt. and on the southern flank of Deer Mountain; a 100ka rhyolite dome. Most recent was the 250 year old eruption on Pahoe Island, in the middle of Mono Lake at the far northern tip of the Mono-Inyo chain.

2.1.2 Structure and tectonics

The dominant local structural trend in the Long Valley region is northwest-southeast. The large Sierran frontal faults such as the Hilton Creek and the Hartley Springs faults trend this direction. Northwest-trending faults that cut the resurgent dome in the west-central caldera are thought to be extensions of the Hilton Creek system (Bailey, 1976). A series of north-south trending faults populates the western moat of the caldera, the southernmost of which cuts the north flank of Mammoth Mt. Such faults likely aid the focusing of magma that was extruded to form the Mono-Inyo volcanic chain (Bailey, 1976; Sampson and Cameron, 1987; Pollard and Aydin, 1988; Miller, 1985). In close geographical relation, is the northeast-trending Discovery Fault Zone (DFZ) of Suemnicht and Varga (1988) which cuts through crust in the western caldera and is also associated with domes and flows of the Mono-Inyo volcanic trend. Ring fracture faults are mapped in the western, northern, and eastern caldera (Bailey, 1989). In addition, recent work by Prejean (2001) delineates several new structures including east-west trending faults in the south moat. They are suggested to be ring fractures, which act as right lateral transforms, transferring strain from west to east between the larger northwest trending Sierran frontal faults. This same work maps a normal slip, north-south fault and a set of parallel, left lateral, oblique slip, north-northeast trending faults just south of the caldera rim in the same vicinity as the northwest trending Hilton Creek Fault. Prejean's faults show no surface expression and are mapped on the basis of precise seismic relocation studies in the greater Long Valley region. Figure 1-2B shows the Long Valley faults from Bailey (1989), Suemnicht and Varga (1988), and Prejean (2001).

Local fault patterns in the caldera mimic regional structures in trend and kinematics. Large northwest trending Sierra range-front normal faults are found both south and north of Long Valley. These include the Little Lake - Owens Valley – Round Valley and Independence Faults to the south and the Silver Lake and Mono Lake Faults to the north. Other northwest-trending faults march eastward from the Sierra, dicing up the crust into horst and graben structure. These include (from west to east), the Inyo Mountains-White Mountains fault zone, the Panamint Valley-Hunter Mountain-Saline Valley fault zone, and the Death Valley-Furnace Creek-Fish Lake Valley fault zone. Smaller northeast trending oblique slip faults such as the Deep Springs and Eureka Valley fault zones south of Long Valley, exist within these larger fault networks. Such faults may act as strain transfer zones between the larger range bounding faults (Dixon et al., 1995; Reheis and Sawyer, 1997; Lee et al., 2001). Selected faults from above are shown in Figure 1-2A.

To the northeast of Long Valley, north-northwest trending faults shift in trend towards the northeast. Gilbert et al. (1968) reported a ubiquitous N6oE fault trend northeast of Long Valley and just to the east of Mono Lake. These faults accommodate left-lateral slip with minor amounts of normal movement and appear to form what Gilbert referred to as a "structural-knee" where northwest-trending faults in the south bend and change direction towards the northeast farther to the north. This region has since become known as the Mina Deflection (Wetterauer, 1977) and is part of the Walker Lane deformation belt (Locke et al., 1940; Stewart, 1980, 1988; Carr, 1984a). The Walker Lane belt of deformation extends from the Sierra in the west to the Walker Line or Lane in Nevada to the east, and from the Garlock Fault in the south to the northern boundaries of deformation in northwestern Nevada and northeastern California (see Stewart, 1992 for a full discussion of Walker Lane boundaries and kinematics). The Mina Deflection faults appear to have activated in the late Cenozoic as they postdate late Miocene- early Pleistocene volcanics, however Wetteraure attributes their trends to pre-Cenozoic inherited structure. In addition to structures mapped east of Mono Lake by Gilbert, other historically active Mina Deflection deformation lies northeast of Long Valley in Nevada. Primary faulting is centered around the east-northeast trending Excelsior Mountain deformation zone, which is in the southern half of the structural knee. The Queen Valley Fault is also located in this broad deformation zone at the northern tip of the White Mountains. Geologic mapping in Queen Valley indicates oblique left-lateral slip on this fault (Stockli, 1998), while a 1934 earthquake on the Excelsior Mountain fault also indicated left-lateral slip.

Farther west in the Nevada portion of the Mina Deflection lies other faulting attributable to Walker Lane deformational processes. Bursik and Sieh, (1989) show several small northeast trending, strike-slip faults in the Mono Lake Basin region that they suggest are facilitating the Mono pull-apart basin. Mapping at the Aurora-Bodie Mining district just to the north of Mono Lake also reveals substantial northeast trending, oblique left slip structures thought to result from reactivation of Mesozoic and older structures from Walker Lane deformation (Burchfiel et al., 1992; Oldow et al., 1989, 2000; Smailbegovich, 2002). Oldow et al., (2000) suggest that the Mono

Basin region acts as a zone of displacement transfer between the southern Eastern California Shear Zone (ECSZ) and the northern extent of the ECSZ (also delineated by Oldow et al., (2000) as the Central Nevada Seismic Zone (CNSZ)).

The ECSZ is a broadly distributed zone of deformation extending from south at the Salton Sea, up through the Garlock Fault region, and north into southern Nevada (Dokka and Travis, 1990a). Geodetic research shows that this zone of deformation is currently taking up approximately 25-29% of the relative plate motion between the Pacific and North American plates (Gan et al., 2000; Dixon et al., 2000; Miller et al., 2001). Large northwest and north trending normal faults in this zone of deformation exhibit right-slip motion in addition to their inherent normal movement, allowing for northwestward translation of the Sierran block in relation to the Great Basin to the east (Dixon et al., 2000). These faults include most of the regional structures mentioned in the beginning of this section. Geodetic work by Dixon et al. (2000) and Miller et al. (2001) suggests that slip on faults within the ECSZ increases to the north and west. It follows that the slip rate on such faults as the Owens Valley Fault is higher than that encountered farther south on such faults as the Death Valley Fault.

In some regions, geologically determined slip rates are much lower than those determined from geodesy. For example, geologically determined slip rates for the Owens Valley fault are approximately 2 $\pm$ 1 mm/yr (Beanland and Clark, 1994), while geodetic rates are 4.0-8.5 mm/yr (Dixon et al., 2000; Miller et al., 2001). This dichotomy suggests that either the geodetic data are not modeled completely, as Lee et al. (2001) suggest, or that the geodetic data captures more recent deformational processes not recorded in the paleoseismic record (Miller et al., 2001). Long Valley

Caldera lies within the geographic extent and influence of Walker Lane/ECSZ deformation, though this relationship has not been explored in any directed way.

2.1.3 Hydrothermal system

Because fault maps presented in this study were created by mapping hydrothermal alteration mineral distributions, a closer look at hydrothermal system chemistry and dynamics is needed. The hydrothermal system has waxed and waned over the millennia with two distinct high discharge periods that scarred the volcanic tablelands of this region and one period of apparent hydrothermal quiescence. Sorey et al. (1978) and Sorey (1985), described a system that reached peak flow and aerial extent at approximately 300ka by dating hydrothermal deposits and by stratigraphic relationship analysis of lake sediments and hot spring sinters (Bailey et al., 1976). Flow and deposition waned post-300ka, but again peaked at 40ka (Sorey et al., 1978, 1985). The hydrothermal system seen today is likely the tail end of this second hydrothermal regime. Oxygen isotope analysis, age dating, and stratigraphic relationships reveal that the initial hydrothermal system source was from the central caldera and was likely driven by thermal input from the Long Valley Caldera magma chamber (McConnell, et al., 1997). The thermal source driving the present day hydrothermal system appears to have shifted to the western caldera beneath the Mono-Inyo volcanic chain (Sorey, 1985; Sorey et al., 1991; McConnell, 1995). Two models for flow dynamics in the caldera have been suggested. Both Sorey (1985) and Blackwell (1985) invoke flow of cold meteoric waters from the Sierran front in the western caldera through or just above the Bishop tuff drawing heat from a magmatic source beneath the Mono-Inyo volcanic chain, and finally, partially discharging along the fault zones of the resurgent dome in the central caldera. The presence of a high temperature (>200°C) reservoir has been confirmed through drilling, fluid sampling, and other geological investigations (Sorey et al., 1991, 1993). Sorey described a shallow flow of thermal waters east from these discharge points in the central caldera, creating a landscape of small creeks and shallow, predominately ephemeral lakes. Blackwell also saw this pattern, but included the presence of an east-west return of cold water from the eastern rim and caldera ring fractures through volcanic fill at depth.

The geochemistry of the hydrothermal system has been resolved by several studies including lithological mapping, geochemical fluid sampling studies, isotopic studies, and alteration mapping and quantification in drill logs. Though the hydrothermal system appears to have been silica saturated in the past, present day chemistry indicates carbonate saturation with localized deposition of travertine (Lipshie, 1976). Sinter deposition was probably much more important in the past. The alkaline to neutral, slightly saline, sodium bicarbonate hydrothermal waters only discharge surficially in the central and eastern caldera, though slightly thermal waters (45°C) discharge from a small spring on Mammoth's western flank at Red's Meadow. Surface temperatures from hot springs in the caldera range from 79-93°C (Sorey et al., 1991). The only acidic waters known to occur in the caldera issue as steam from fumaroles on the northern and southern flanks of Mammoth as well as a few places within the western and central caldera including Basalt Fumarole and Fumarole Valley. The lack of surface water discharge in the western caldera is likely due to the higher topography encountered in this region relative to the caldera floor to the east (Sorey et al., 1991).

The hydrothermal alteration assemblages studied by Flexser (1991) are dominated at depth by illite, smectite and illite/smectite interlayered clays with secondary alunite, kaolinite, and opal. McConnell et al. (1997) also noted calcite, pyrite, quartz, kspar, albite, chlorite, and epidote in the Long Valley Exploratory Well (LVEW) core from the resurgent dome. Such assemblages are typical of intermediate temperature supergene and hypogene alteration environments described in the ore deposit literature. In general, young volcanic systems such as Long Valley are thought to be proto-epithermal mineral deposits. Study of epithermal-hosted alteration aids in prediction of mineralization in Long Valley.

Various authors have reported small, localized mapping endeavors of surficial hydrothermal alteration (including Chelikowsky, 1940; Cleveland, 1962; Rinehart and Ross, 1964; Bailey, 1976, 1989; Suemnicht and Varga, 1988; Sorey, 1985, 1991) Their mapping revealed the presence of kaolinite, alunite, montmorillinite, calcite, and sinter, all of which are found in the opalized, argillized, and advanced argillized zones of epithermal mineral deposits. However, identification of alteration in the field can be quite difficult. Alteration minerals tend to be very fine grained and of similar colors and grain size. They are often distributed diffusively and hence difficult to map or to see with the naked eye. Even lab-based XRD analysis proves difficult for most clay. In addition, the large size of Long Valley renders field-based synoptic alteration mapping, impractical. Hence, our current knowledge of the distribution and identification of alteration assemblages caldera-wide, is poorly known.

2.2 Remote sensing

2.2.1 Previous Long Valley studies

The material-mapping abilities and synoptic, multi-temporal, system scale coverages of satellite and air-based sensors makes remote sensing a standard tool within most volcanological monitoring and study programs. However, Long Valley caldera has received limited geological study via standard remote sensing techniques. Landsat TM (Thematic Mapper)-based volcanic lithological mapping was completed by Levine (1985). He utilized various spectral band ratioing techniques to discriminate volcanic flows from one another in the greater Long Valley region. Del Grande (1985) utilized dual channel air-based TIR (thermal infrared) data in attempts to map heat flow anomalies in the caldera. She coupled airborne temperature surveys with field temperature surveys from core and drill holes and shallow thermistors to produce three-dimensional heat flow anomaly maps. However, shallow convective systems are quite hard to characterize, and extrapolating surface measurements several hundreds of meters into the crust is uncertain. Fialko, et al. (2001) completed an InSAR (Interferometric Synthetic Aperture Radar) study of Long Valley, which delineated the focus of current re-inflation in the central caldera as an inclined prolate spheroid at a depth of 7-9 km. Finally, Hausback et al. (1998), De Jong (1998), and Sorey et al. (1998) performed initial hyperspectral imaging-based studies on Mammoth Mt. that mapped the locations of CO_2-induced tree-kills on the volcano's flanks, while DeJong and Chrien (1995) attempted to map the CO_2 emissions directly, but with limited success.

2.2.2 Hyperspectral remote sensing

Goetz et al. (1985) introduced the geological world to hyperspectral imaging, ushering in a new age of remote sensing. Sampling the electromagnetic spectrum tens to hundreds of times in narrow, contiguous, wavelength partitions produces a complete spectral signature that can be measured from an earth material (see Fig. 1-3). The reflectance or emittance of radiation from any material produces spectral signatures that are often unique to that particular material; e.g. the interaction of light and/or heat with crystalline minerals produces a set of absorptions and reflectances unique to that crystalline structure. Absorptions may be due to charge transfers and molecular bond bending, stretching, and vibrations. In addition, significant absorption of light and heat energy occurs within the Earth's atmosphere with H_2O, CO_2, NO_2, O_2, and O_3 being the dominant absorbing molecules; corrections for such atmospheric absorptions are made in radiative transfer models that are discussed in section 3.2.

Hyperspectral measurement and quantification of the interaction of radiance with the Earth's surface is done with imaging spectrometers (also known as hyperspectral imagers as they are also known). Handheld spectroradiometers are used in the field as well as in the laboratory under controlled lighting conditions. Imaging spectrometers are both air and space-based, though the only space-based hyperspectral imager, Hyperion, which was launched in November 1999, is considered experimental with a limited lifetime.

2.2.3 Hyperspectral imaging in volcanology

Hyperspectral imaging is a young technology that has been used in volcanological studies on a limited basis. To date, several studies have been completed that map hydrothermal alteration minerals in Long Valley caldera (Martini et al., 1999; 2000; 2001), but with limited interpretation and synthesis of the hyperspectral data and other geophysical and geological data from the hydrothermal system. Hyperspectral work at other Tertiary hydrothermal systems indicates that important information regarding the geochemistry, temperature, and discharge patterns of hydrothermal systems can be determined (Livo et al., 2000; Crowley et al., 1999; Rockwell et al., 2002; Kruse, 2000). Livo et al. (1999) mapped hydrothermal alteration in the Yellowstone Basin and linked these maps to other hydrological and geochemical studies in the region. Crowley et al. (1999) mapped summit and flank hydrothermal alteration on Mt. Shasta, and combined these data with DEMs to produce flank stability maps that may indicate future loci for debris flows and/or lahars. Rockwell et al. (2002) produced alteration mineral maps of the Marysvale Volcanic Field, and combined these data with XRD analysis. Kruse (2000) mapped hydrothermal deposits in Steamboat Springs, Nevada, and determined a new temporal evolution for the formation of these hot springs.

3.0 Hyperspectral imaging in Long Valley Caldera: Methods

3.1 Image acquisition

Before 1999, there were no hyperspectral images of Long Valley Caldera as a whole, although several NASA sponsored Advanced Visible Infrared Imaging Spectrometer (AVIRIS) missions had previously covered the much smaller Mammoth Mountain area and some areas in the eastern caldera. The first AVIRIS image of Mammoth Mt. was taken in 1992, with subsequent images taken yearly after that.

This AVIRIS dataset has an impressive annual temporal resolution, with a spatial resolution of approximately 17 m. To obtain a finer pixel resolution for vegetation communities as well as primary hyperspectral coverage of the caldera, an acquisition was flown on September 7, 1999 with the Australian HyMap sensor (Integrated Spectronics, Ltd.). The acquisition covered approximately 540km^2 between latitude of 37° 30" to 37° 36" and longtitudes of 118° 42" to 119° 04" W (See Fig. 1-4). It consists of seven east-west flightlines (2.3 km x 32 km) with a spatial resolution that varies from 3 to 5m depending on local topography (elevation ranges from 2070m on the caldera floor to about 3300m in the Sierra Nevada range and at Mammoth Mountain). HyMap samples the electromagnetic spectrum from 450 to 2500 nm in 126 separate, but contiguous, wavelength bands from 13 to 17 nm wide. Signal-to-noise ratio (SNR) is well over 1000:1 for most wavelength regions (Cocks et al., 1999). The instrument was flown aboard a twin-engine Cessna with complete radiometric and spectral calibration and simultaneous DGPS data acquisition. The dataset was acquired as part of a group-shoot including several other U.S. governmental, educational, and commercial entities and was organized by Analytical Imaging and Geophysics (AIG) in Boulder, CO, USA and the HyVista Corporation in Sydney, Australia. HyMap data is the primary source of imagery used in this study.

3.2 Image processing

Primary processing and analysis were done within the ENVI software environment. The data were received as radiances (mW/cm^2/sr/nm) and were calibrated to reflectances. Once calibrated, the data were subjected to classification and mapping algorithms.

3.2.1 Correction to apparent reflectance

Several steps are needed to produce well-calibrated apparent reflectance data from an imaging spectrometer. These steps must be completed before classification and mapping algorithms are applied to the data. Data were received as radiances, and were then calibrated to apparent reflectances via a radiance transfer model called ATREM (Atmospheric Removal) (Gao, 1993). This model uses variables gleaned from the image headers such as elevation of flight, average scene elevation, date, time, location and general ecosystem character to model the atmospheric column on a pixel-by-pixel basis. Concentrations of atmospheric elements including H_2O, CO_2, O_2, and NO_2 are then modeled and removed from the column. Changes in topography were not modeled, as only the average scene elevation entered at the front end of this algorithm is used. Also, all gases are modeled as being evenly mixed throughout the column. The end product from ATREM is atmospherically corrected, reflectance data. ATREM has limitations, and several artifacts may remain in the data after correction. One significant artifact is an over-correction in blue wavelengths due to mis-modeled path radiance in this part of the spectrum. This over-correction may be addressed by forcing the spectrum in the blue wavelength region to conform to known path radiance values. Other artifacts are addressed in a similar fashion. Normally, a spectrally homogeneous region is found within bounds of the image acquisition and is spectrally sampled in the field with a field spectroradiometer. The average spectral signature of this region is compared to the average spectral signature of those pixels in the imagery that correspond to the homogeneous region. Details of this calibration technique are found in Clarke, 1995. Our images were acquired opportunistically with no ground measurements possible on the day of overflight. Instead, we applied an EFFORT (Empirical Flat Field Optimal Reflectance Transformation) correction. This is a statistically driven algorithm that removes artifacts by spectrally smoothing the data (Boardman, 1998). Only EFFORT-corrected apparent reflectance data were used in this study.

3.2.2 Initial spatial data reduction

ENVI analyses use statistically based algorithms for spatial and spectral subsetting of data to isolate unique spectral populations, or endmembers, within an image. The HyMap data was initially subset into two spectral chunks, a Visible-Near Infrared (VNIR) chunk with wavelengths ranging from 0.45-1.9 μm and a Shortwave Infrared (SWIR) chunk with wavelengths ranging from 2.0-2.5 μm. Though most materials have spectral responses in the 0.45-2.5 μm wavelength region, certain regions are more characteristic of certain materials than others. As an example, clays possess very diagnostic absorptions in the 2.0-2.5μm range, but their signatures are virtually flat in the VNIR. Hence, we use the SWIR chunk to study clay. Sub-aquatic materials on the other hand, have virtually no response in the NIR and beyond due to the severe attenuation of longer wavelengths in the water column. Hence, we study aquatic environments with visible and small amounts of NIR light only.

Each flightline was approximately 32km long and 2.5km wide. This flightline was then divided in half due to disk space issues. From this point, each flightline was subset into study areas of interest with variable geographical sizes depending on the phenomena or feature of study. Entire flightlines were not processed for two reasons. First, even half-flightlines are upwards of 600 MB. The amount of CPU required to process such enormous datasets discourages such an activity. Second, and perhaps more importantly, spectral variation within a scene is dependent on the size of the scene. The larger the scene, the higher the spectral variability encountered. As an example, the hydrothermal alteration mineralization at the hydrothermal area of Hot Creek was mapped using a scene only 4km long and covering only the area in the direct vicinity of Hot Creek. Inclusion of alteration zones farther west in Fumarole Valley could dampen the signal of Hot Creek mineralization if there were higher concentrations of it, or if the mineralization was more or less pure than at Hot Creek. In general, specific zones of study have better discriminatory values than large subsets or whole flightlines.

3.2.3 Spectral data reduction: MNF

Each scene of interest was processed with a set of statistically driven algorithms within ENVI. The complex spectral variability inherent in the hyperspectral dataset was manipulated with a principle components-like algorithm called the Minimum Noise Fraction (MNF) transform. In general, principle component analyses suppress noise and enhance image signal. Individual signal images tend to represent broad material classes, and allow for simple, first order material classifications within an image. The Minimum Noise Fraction (MNF) is a two-step cascaded principle components algorithm contained within ENVI©. The noise in the data is first whitened resulting in uncorrelated noise in every band and unit variance. Secondly, the data are treated to a standard principal components transform resulting in a set of new n-dimensional axes (Green et al.,1988). As we are only interested in those bands with the most signal and coherence, those bands containing mostly noise are removed from further processing. MNF analysis with HyMap data generally yielded an average of 20-30 signal-rich, MNF bands.

3.2.4 Secondary spatial reduction: PPI

In order to determine endmembers in a less subjective and more quantitative way, a spatial reduction ENVI algorithm was run on the data. The Pixel Purity Index (PPI) algorithm finds the most spectrally pure or extreme pixels within a dataset. These purest pixels usually represent the dominant scene materials, and are used to generate several different kinds of material classifications. N-dimensional scatter plots of pixels are repeatedly projected onto a random unit vector. The extreme pixels, which fall at the end of the unit vector, are recorded for each projection. The total number of times a pixel is marked as extreme is calculated. Those pixels with the highest numbers, are the purest (ENVI manual, AIG LLC, 1997). This spatially reduced the dataset significantly. Individual scenes processed in this study ranged from approximately 500,000-1,000,000 pixels. The PPI algorithm reduced these numbers to anywhere from 800-1500 pixels depending on the thresholds used. The pixels maintain their geographic location within the original image. Purest pixels were then projected into the n-dimensional space of the N-Dimensional Visualizer within ENVI. This tool allows the user to visualize hyperspectral data in its full dimensionality. Most scenes in this study were viewed in approximately 20-25 dimensions. Endmembers were delineated from multi-dimensional plots and exported as spectral signatures into a spectral endmember library. These signatures were then used in subsequent classification efforts.

3.2.5 Image classification: MF

Matched Filter was the primary algorithm used in classification efforts. This algorithm determines the abundances of endmembers using partial unmixing routines. All the representative materials within a scene do not need to be known. Classification results produced individual rule abundance images instead of full classification maps produced by other less sophisticated mapping algorithms contained in ENVI. The rule abundance images were reduced further by applying a threshold on the values of each individual endmember class image in order to enhance those pixels with the best matches to the given spectral signatures from the endmember libraries. Rule abundance images for each material of interest were geocorrected using DGPS-based files collected from the time of overflight. The pixels with values best matching the given spectra in each class image were exported to ENVI vector files. These vector files were then overlaid on a myriad of other geospatial products, including the original HyMap data, other geocorrected remotely sensed data, and digital map products such as DRGs, DLGs and DEMs. Most spectral mapping data in this study is shown overlain on either geocorrected true-color HyMap scenes or shaded subsets of the 10 meter Long Valley USGS DEM.

4.0 Image analysis: Results

I’ve produced sets of synoptic mineral maps for Long Valley Caldera. The ENVI-based mineral maps were created by classifying individual spatial chunks from all seven flightlines. The data are too large to discuss on a scene-by-scene basis.

Sampling and studying a region at system scales instead lends itself to synoptic classifications and synthesis. General trends in mineralization measured spectrally throughout the caldera are discussed. A few specific regions are singled out and discussed more thoroughly in order to illustrate caldera-scale processes and phenomena.

4.1 Mineralization

I detected approximately 28 minerals in the Long Valley hyperspectral data. (Table 1-1). The more minor minerals mostly include different kinds of evaporites and sulfates found in the eastern third of the caldera, but also several silicates found in very specific locations, and nowhere else (such as the feldspar, albite). Though different minerals dominate different regions of the caldera, a few minerals are more or less ubiquitous throughout the entire caldera. One of these minerals is kaolinite, a potassium-rich clay. Kaolinite can form deutirically, however when found in association with higher temperature sulfates or other clays, it may be hydrothermal in origin (forming at temperatures of 100-200 °C; never exceeding 220 °C). The sulfate alunite found in lesser concentrations, but widely mapped. Alunite forms at temperatures of 100 –230° C; generally exceeding 200°C, and commonly occurs in advanced argillic phases of alteration mineral assemblages with other high temperature minerals such as pyrophyllite. It is also generally associated with kaolinite (or one of kaolinite's higher temperature polymorphs such as dickite or nacrite). Commonly, alunite is also associated with kaosmectite, montmorillinite, and other high temperature clays. However, there are many places where smectitic clays are mapped that have no concurrently mapped alunite. Minerals such as montmorillinite are much more pervasive in the caldera than the higher temperature minerals. The smectite montmorillinite forms at 100-200°C, generally on the lower end of that range and never exceeding the 200°C threshold. Chlorite was common, but because threshold temperatures for chlorite formation are broad, this mineral is less useful for hydrothermal temperature estimations. In general, chlorite is part of a widespread intermediate temperature propalytic alteration assemblage. The other major group of minerals mapped include calcite, amorphous silica, and hematite. The calcite is generally in the form of terraced travertine deposits (confirmed with field and map checking efforts rather than spectral feature analysis), while occurrences of amorphous silica are more complex. There are some primary hydrothermal sinter deposits, but pervasive opalization of other hydrothermal minerals has produced amorphous silica. Hematite is found as an oxidation product of iron-rich minerals within mafic rocks throughout the caldera, but it is also found in conjunction with hydrothermal minerals including amorphous silica. In a few locales, hematite occurs as gossans, an iron oxidation of sulfide deposits. In this form, hematite indicates fairly high temperatures.

Lesser mineralization includes several evaporites/borates such as trona, tincalconite, and gypsum. These are generally found in the eastern half of the caldera, in the Alkali Flats region and outflow zone of Little Hot Creek. Dolomite is also found in this region, usually near to hot creeks and pools. Limited jarosite is found on the flanks of Mineral Hill, the site of gold and silver mining for at least 150 years. Albite and epidote are also found in this same vicinity. Both minerals indicate high formation temperatures in the potassic phase. Two minerals with limited spatial extent, but important implications are buddingtonite and pyrophyllite. High temperature (>230°C) pyrophyllite occurs on the flanks of Mammoth Mt. and is limited quantities north of Hot Creek. The ammonium feldspar buddingtonite is found near Casa Diablo geothermal plant and north of Basalt Fumarole in the western caldera. Buddingtonite is thought to be deposited during vapor phase alteration and is the ammonium equivalent of the high temperature alkali feldspars. It usually occurs with smectites (Felzer et al., 1991).

Hydrothermal processes that form many of the minerals listed in Table 1 include both fumarolic discharge of superheated volcanic gasses and surficial discharge of hot waters into pools or creeks. Degassing or liquid discharge usually occurs along some crustal weakness; such as a contact boundary, fracture, or fault. Continuous discharge of gas and hot water over many years eventually alters the soil and rock along contacts, fractures and faults, which tend to be linear. Thus linear distributions of kaolinite and other hydrothermal alteration minerals discussed above, may be used as a proxy for fault and fracture distribution mapping within hyperspectral imagery.

4.2 How accurate is hyperspectral imaging in Long Valley?

The accuracy of hyperspectral imaging for mineral detection and identification has been addressed in many studies by various workers, though most rigorously by researchers at the USGS Spectroscopy Lab in Denver. Many early to mid-1990s hyperspectral image acquisitions were analyzed and verified by spectroscopists at the Spectroscopy lab using a combination of handheld field/lab spectroradiometers, whole-rock XRD analysis, and SEM techniques (eg. Swayze et al., 1992; 1996; King et al., 1995). Early work such as Swayze et al.'s study of hyperspectral imaging at

Cuprite, Nevada showed very good accuracy between mineral identifications with spectroscopy versus XRD. Twelve out of 17 samples were positively identified with XRD as being the same as what spectroscopy measured. In most cases, the other five samples differed by degree of crystallinity and by idenfication of endmembers (eg. spectroscopy indicated K-alunite, while XRD indicated Na-alunite). The USGS, and a myriad of other researchers, have also carried out extensive field programs verifying mineral maps by using spatially corrected image-mineral maps, gps, and handheld field spectroradiometers. Results of these field checking expeditions are usually quite good, though false positives do arise. Many false positives are due to geocorrection issues, i.e. the mapped mineral does exist, but it's location is off by several tens of meters leading to an inaccurate false positive. Control on this type of error will increase with better geocorrection hardware and algorithms.

The accuracy of the mineral maps in Long Valley caldera was checked in three separate ways: field checking using a portable spectroradiometer, XRD analysis of selected field samples, and comparison of surface alteration maps with down-hole well alteration data.

Five dedicated field-checking surveys were conducted in the caldera from 1997 to 2002. Selected random sampling of points were scattered over regions of interest on georectified mineral distribution maps. These maps were taken into the field with a portable ASD-FR (Analytical Spectral Device-Full Range) spectoradiometer (AIG, LLC, Boulder, CO, USA). Points on the map were located using a 12 channel Garmin GPS, and measured using the ASD. The identification of the field spectra was determined using USGS spectral libraries and the Spectral Feature Fitting algorithm within ENVI. Over a hundred measurements of this type were made over the various field seasons, and accuracy was high. Major sources of error appeared to be geocorrection issues, and not the mapping or identification algorithms. As an example, mineral mapping revealed calcite in a particular pixel within Hot Creek Gorge in the central caldera. Upon visiting the site located with the GPS, no calcite was present. However, extensive beds of travertine (hydrothermal calcite) lay ten meters to the north. This either implies diffuse carbonate within the soils of the original pixel, or mis-registration by upwards of two to three pixels (if spatial resolution is at 5 meters). In general, field checking revealed few false positives. False positives were generally due to geocorrection issues and diffusive distribution of some mineralization.

XRD analysis was also done on selected samples from throughout the caldera. Twenty-six samples were powdered and crystallinity was determined. Of the twenty-six, nine samples weren't crystalline and thus not identifiable with XRD. Table 2 shows the results of the XRD analysis, along with the spectrally determined identification of the dominant mineralization of the whole rocks (taken before powdering). Fourteen of the seventeen crystalline samples had a XRD identification that matched the spectral identification, though five of these to a lesser degree. Three of the seventeen were false positives. One of the false positives was identified by XRD as quartz, which VIS-NIR-SWIR spectroscopy can't identify, because the spectral signature is flat in the SWIR. Another false positive was identified as quartz by the XRD, but as amorphous silica by spectroscopy. It is possible the two minerals coexist in the same rock, and the spectral measurement missed the quartz part of the rock. The final false positive was identified by XRD as feldspar, but as kaolinite by spectroscopy. This mis-identification remains unresolved. All of the non-crystalline samples were identified by spectroscopy as amorphous silica, with the exception of sample R which also appeared to have hematite, and sample DD which appeared to be montmorillinite. At first order, the XRD analysis successfully echoes spectroscopy results. Mis-identifications may be real, or due to differences in measurement areas with each respective method (i.e. areas of rock measured with spectroscopy were different than those measured with XRD).

The final assessment of hyperspectral imaging's general accuracy was accomplished by comparing surface alteration in a 150-meter radius around previously drilled well and core holes around the caldera, with alteration, temperature, and pH at depth. The outcome of this analysis is discussed fully in Chapter 2, section 5.3.1.

4.3 Results of image analysis at a local site scale

The following mineral mapping results are from four sites around the caldera (indicated on Figure 1-2B). The derived mineral distributions are shown overlaid on either the original HyMap imagery, or on shaded relief 10 m USGS DEMs. All the imagery and mineralization are geospatially corrected.

4.3.1 Results of image analysis – Mammoth Mountain

Though the presence of hydrothermal alteration on Mammoth was known previously, the character and spatial distribution of the alteration assemblages was poorly known. A true-color HyMap image is shown in Figure 1-5A. The bleached summit of Mammoth and surrounding trees are clearly seen in this 4 m data. Figure 1-5B,C,D show the MF-driven mineral mapping results for the same portion of Mammoth Mt. Three separate mineral abundance images are shown; kaolinite (mixed with its polymorph halloysite) (Figure 1-5B), alunite (1-5C), and montmorillinite (1-5D). These abundance images are color-coded such that red is the best match to endmember spectral signatures, and blue/purple are only partial matches. All these images are spatially uncorrected, with north towards the top of the page. The mineral abundance in Figure 1-5C maps a high density, localized distribution of alunite, while the kaolinite abundance (Figure 1-5B) is more widely spread. Montmorillinite (Figure 1-5D) is not as spatially coherent as either the kaolinite or alunite, and tends to be widely spread over the mountain, however it is localized in a few spots.

Figure 1-6 is a composite of several minerals mapped in a subset of the region shown in Figure 1-5. A previously mapped fault is indicated by the solid orange line (Bailey, 1989), paleo volcanic vents as yellow ovals and a CO_2-induced tree-kill as a green square. The three mineral distributions of Figure 1-5 are included in Figure 1-6, but Figure 1-6 also incorporates hematite. This hematite signal is likely a gossan (iron oxides over rich sulfide deposits) deposited in a hydrothermal manner. Hydrothermal alteration occurs along the NW-trending fault mapped by Bailey in 1989, that is a part of the Long Valley caldera ring fracture zone. Bailey didn't map a parallel fault just to the northeast (the dashed NW lineament) that runs through areas of dense hydrothermal alteration and two paleo-vent structures.

Two northeast lineaments cut through the central area of alteration. Mapping is based on spectrally determined linear distributions of alteration, as well as fieldwork. These linear distributions are comprised of very high temperature alteration assemblages, and are not linear streamers of float from above. Spectrally, there is no doubt of the alteration mineral's identity, and physically, these deposits are in-situ, thick profiles of steam-altered soil and rock. The degree of alteration also indicates that a vigorous and long-lived vapor phase system existed on the southwest flank at one time. The southern NE-trending lineament extends to the southwest through a zone of CO_2 induced tree-kill. In-situ CO_2 flux measurements in this possible fault zone also showed high rates of flux along the entire length of the mapped structure (Rogie, pers. comm., 2002). To the northeast, this NE-trending zone appears to run through a paleo-vent structure mapped previously by Bailey (1989). This structure is acting as a conduit for gases and magma.

4.3.2 Results of image analysis – the Discovery Fault Zone

The smaller volcanic domes known as Earthquake Dome, Dry Creek Dome, and Mammoth Knolls Dome lie just to the northeast of Mammoth Mt. (Figure 1-7). Suemnicht and Varga (1988) suggested that the western boundary of these domes is cut by northeast trending faults collectively known as the Discovery Fault Zone (DFZ). Figure 1-8 illustrates the proposed DFZ, and the inset magnifies that region around Dry Creek Dome, which is cut by the main fault of the DFZ. The location of the DFZ study area is shown on Figure 1-2.

Figure 1-9 shows the results of MF analysis in the region of the DFZ. Though this area is steep and highly wooded, mineralization was detected and mapped. Kaolinite, alunite, nacrite, and amorphous silica are shown in this figure. Small amounts of other minerals were detected, but are not shown for clarity reasons. The amount of alunite and kaolinite in the vicinity of the main structure associated with the DFZ (see inset on Figure 1-9) is actually quite small (Site A). The alteration is localized discretely along the main fault zone, however regionally, alteration is far less localized. Diffuse alunite, kaolinite, and silica is found to the east of the main

DFZ fault within a broad zone. This alteration coincides with several lesser faults of the DFZ, though the alteration distribution is more diffusive than that mapped along the main Discovery Fault. Less alteration is observed within the caldera boundaries directly to the west of the main Discovery Fault. The exception is the Inyo Craters region where significant kaolinite, alunite, and nacrite is associated with young phreatic pits (Site B on Figure 1-9). The Inyo Craters and the south flank of Deer Mt. are altered mostly to kaolinite and minor alunite, while Crane Flat to the west is covered in dense nacrite and lesser kaolinite/alunite. Farther west, out of the caldera, the San Joaquin Ridge has abundant alunite and minor nacrite and kaolinite (Site C on Figure 1-9). Finally, small linear distributions of amorphous silica with minor kaolinite are mapped towards the southwest of the image (Site D on Figure 1-9) with only partial association with previously mapped faults.

4.3.3 Results of image analysis – Hot Creek

Hot Creek is located in the central caldera (see Figure 1-2). The waters are alkaline, slightly saline and bicarbonate rich. Temperatures reach approximately 93°C, (boiling point at this elevations). The creek discharges 80% of the hydrothermal waters in the caldera and occurs along several faults that cut the creek in a northwest trend. Image analysis reveals evidence of an east-west trending fault that cuts the creek.

For simplicity, only three minerals are shown overlain on a true-color mosaic of three subscenes of HyMap data in Figure 1-10. Kaolinite is the most abundant mineral of the three, and is localized primarily along previously mapped faults (red lines). There are several locations where alunite co-occurs with kaolinite. This happens most notably along Hot Creek (Site A on Figure 1-10) and along the north-

northwest trending faults that run along the eastern flank of the caldera resurgent dome (Site B on Figure 1-10). Several areas of kaolinitic alteration do not coincide with previously mapped faults, including one east-west structure that cuts through the center of the mosaic (Site D on Figure 1-10), and two other compelling but incomplete east-west trending linear distributions of kaolinite occur both to the south (site C on Figure 1-10) and north (Site E on Figure 1-10) of the central feature.

Examining abundance fit images such as those discussed in section 3.2.5 produces the linear mineral trends shown above. The fit images for major alteration minerals are threshold in order to highlight only those pixels with the best matches to given spectral signatures. Most of the linear trends were mapped using a mixture of kaolinite, alunite, hematite, and amorphous silica. Patches of alteration that appeared to spatially align, and did not coincide with any known contact boundaries, were connected to one another with a line that may represent a fault/fracture of some kind. Figure 1-11 shows a straightforward example of this process done in the Hot Creek region. Bailey's faults are easily seen using linear trends of alteration mineral assemblages, as are several previously unmapped structures including the east-west lineaments. These east-west lineaments were visited in the field. Both sites D and E have topographic expressions that resemble fault scarps, though no sign of offset was found (Figure 1-10). Site D, called here Cow Fault, also has several lone trees growing along the linear trend of the possible fault, suggesting an enhanced zone of permeability. Field spectra taken at five sites confirm the presence of both kaolinite and alunite in locations measured by the hyperspectral HyMap imagery. East-west structural trends appear to be more common in the caldera than previously thought.

The distribution of amorphous silica in this scene is diffuse, though much of it is probably associated with zones of ancient hydrothermal discharge. Some amorphous silica is found in regions of present discharge, but the geochemistry of the waters in these areas doesn't generally support present day silica deposition. Most of the amorphous silica found in this scene is to the east in the Alkali Lakes region (Site F in Figure 1-10). The waters discharging in this area are quite cool compared to waters at Hot Creek or further west.

4.3.4 Results of image analysis – the South Moat

The southern half or moat of the caldera is home to extended periods of vigorous seismic activity, especially over the past 20 years. Although several faults have been suggested on the basis of this seismicity, very few have any surface expression. Such faults are thought to focus either hydrothermal fluid or magma transport or both. Hyperspectral mineral analysis reveals several east-west zones of mineralization in the southern moat that coincide with zones of previously recorded seismic activity.

The southern moat (Figure 1-12), is defined in the south by the Sierra Nevada and the north by the southern flank of the resurgent dome (see Figure 1-2 for location). Kaolinite and alunite are mapped along the NW-trending resurgent dome faults that form Fumarole Valley as well as faults that bound the Casa Diablo geothermal field. Much of the kaolinite seen in this image coincides with previously mapped faults, with several exceptions. The linear distributions of kaolinite right at the base of the southern flank of the resurgent dome (letter A on Figure 10) do not correspond to any previously known structures. In addition, kaolinite approximately 7 km to the west of Site A is an anthropogenic excavation at this site (Site B on Figure

1-12). Such subsurface kaolinite pits are seen at other locations around the caldera, and hint at the likely composition of caldera soils in this region at depth.

The linear mineral distributions in the western half of the image consist predominately of amorphous silica and hematite. Hydrothermal mineralization has not been seen before in this area, probably due to abundant cover of glacial till and the difficulty of field mapping such mineralization.

An additional mineral shown in Figure 1-12 is buddingtonite, a feldspar altered by ammonium bearing waters, indicating very high temperatures. Its distribution coincides with known fumarolic zones, but not necessarily with any previously mapped structures. Buddingtonite is found near to northwest trending resurgent dome faults, however it is also found within the general east-trending zone of faulting which may channel hydrothermal flow in the southern moat. The high temperature of formation for buddingtonite supports a long-lived zone of hydrothermal flow at these points.

5.0 Synthesis with local and regional geology: Discussion

5.1 Hyperspectrally-derived fault and fracture maps: Local scale

In each example presented in section four, both previously known faults and new lineaments were found. Each local site reveals important information about the structural system in an active volcanic region that can be mapped with hyperspectral data by detecting and mapping of linear alteration zones. New insights into site-specific processes and phenomena at these local sites emerge, while the Long Valley-wide structure is more finely conceptualized.

5.1.1 Mammoth Mt.

Wholly new structures were identified on the flanks of Mammoth Mt. that suggest refinements for models of the structural framework for Mammoth Mt. and the caldera of which it is a part. The most intriguing of these new structures is defined by the narrow zone of alunite-kaolinite mapped on the southwest flank (see Figure 1-5, 1-6a). This feature likely corresponds to a paleo-fumarolic zone, as alunite is commonly deposited from the gaseous state at low pH levels and high temperatures. Though kaolinite may form deutirically, its close spatial association with alunite precludes this hypothesis. Rather the kaolinite also probably formed from the gaseous phase at slightly lower temperatures than the alunite. Both minerals represent an argillic to advanced argillic alteration system. The montmorillinite mapped in this scene is a smectitic clay formed at much lower temperatures than the kaolinite and alunite discussed above. It is spatially less coherent than the alunite and kaolinite; found all over the mountain and not localized. Montmorillinite and other low-temperature smectites are generally part of pervasive, regional, low temperature alteration phases, and may or may not indicate abnormal geothermal gradients. The association of this montmorillinite with the kaolinite-alunite assemblage however, suggests a thermal origin.

This particular suite of high temperature alteration minerals, and their fairly linear spatial trend, suggests this area is a paleo-fumarolic zone aligned with a portion of crust that has high permeability and a possible structural weakness. Fieldwork on the southwest flank revealed steep slopes, and thus some of the linear spatial pattern is likely due to downslope failure (float). However, further field inspection revealed a very coherent linear structure in this region, not explainable by float. It is not known whether this fracture has fault slip, as no slip indicators were found. A slight northeast-ward extension of the structure would bring it through a zone of paleo volcanic vents and cutting over the northwest trending fault zone mapped by Bailey (1989). Several researchers have studied the intersection of faults in the western caldera. Suemnicht and Varga (1988) documented intersecting fault sets along the Mono-Inyo volcanic chain. In many locations of volcanic domes and other eruptive centers, they found prominent orthogonal to sub-orthogonal fault intersections. The intersection of faults is a well-documented mechanism for enhancing vertical crustal magma migration. On the SW backside of Mammoth, the intersection of the northeast trending fault with the northwest trending ring fracture faults of the caldera may have served as the initial structural weakness that allowed for initial formation of Mammoth Mt. The southwest section of this northeast trending structure (see Figure 1-6a) also intersects a known CO_2-induced tree-kill zone (Reds Drainage Kill). Sorey et al. (1998) suggested that CO_2 is focused and degassed along pre-existing structures on the volcano. The intersection of the northeast trending structure and the ring fractures is a likely candidate for gas flux on this part of the mountain.

Figure 1-6 shows three new lineaments mapped on the southwest flank, and one previously mapped fault intersecting nearly orthogonally. Possibly the entire summit of Mammoth is an intersecting set of fault zones rather than one discrete ring fracture zone. Northeast trending faults and fractures are scarce in the caldera, but those found on the southwest-flank mimic the trend of other structures in the western caldera, most prominently, the DFZ of Suemnicht and Varga (1988) which lies ~4 km northeast of the southern flank. Such structures may provide a framework for the northeast-trending southwest-flank fault shown dashed in Figure 1-6a.

5.1.2 The Discovery Fault Zone

With this in mind, we sought to test the presence of the DFZ, which supports the existence of the southwest flank fault. The existence of the DFZ, as defined by Suemnicht and Varga (1988), hinged largely on the presence of alunite along the main fault of this zone. Though difficult to find and identify in the field, alunite is easily identified with imaging spectroscopy.

The faults shown in Figure 1-8 were mapped primarily from aerial photo interpretation and fieldwork, with alunite mapped along a few fault surfaces within the DFZ. Suemnicht and Varga (1988) suggested that this alunite indicated past fault movement and evidence for deep hydrothermal circulation. They further suggested that the DFZ structures are inherited basement flaws beneath the Long Valley region, and that the intersection of the northeast trending DFZ structures with the north-south trending faults along and within the Mono-Inyo volcanic chain serve as zones for enhanced vertical permeability for both hydrothermal discharge and magma. Thus the existence or non-existence of the DFZ is important for forming accurate models of how and where parasitic volcanism occurs within the western moat of the caldera, including the genesis of Mammoth Mt. and possibly Long Valley itself.

The main Discovery Fault of the DFZ was detected remotely and mapped spectroscopically, however it was more difficult than other mineral mapping in the caldera. We believe the scarcity of alteration mapped in the hyperspectral imagery at the DFZ is due to several factors. First, the steepness of this region reduces the imagable area for analysis, thus making alteration far less detectable. Second, the face of Dry Creek Dome is densely vegetated with old growth conifer forest whose canopy is a severe hindrance to surface mineral mapping. Third, there is probably very little alteration along this fault compared to other locales, making detection difficult. As an example, there is much greater alteration around the young Inyo phreatic craters than on the Discovery Fault. This may be due to the relative level of activity that formed each respective alteration zone, as well as to the relative ages. The DFZ alteration is likely older than the Inyo crater alteration. This hypothesis is loosely based on the respective ages of volcanic activity involved (Inyo Craters ~600 years; Dry Creek Dome ~4000 years). No age-dating of these minerals has been done. Field observations found that alunite and kaolinite do exist where the hyperspectral imagery indicates it. XRD analysis discussed in section 4.2 also confirms the existence of alunite at the main northeast-trending DFZ structure. In addition, fault slickenlines were clearly visible on the rock outcrops coinciding with the fault zone, indicating oblique slip in the NE-SW direction. Recognition of the above alteration without the hyperspectral mineral alteration maps would be very difficult, as Suemnicht and Varga reported.

Mineral mapping in the DFZ region reveals more than just the existence of the main Discovery Fault. On a local scale, quite a bit of alunitic alteration is found outside the caldera on the San Joaquin Ridge. This alteration falls along part of a previously mapped fault and then continues along the same trend to the southeast where no fault has been mapped. The San Joaquin ridge has not been field checked, but the alteration there may predate the Long Valley Caldera hydrothermal system. The alteration seen directly at Site C (Figure 1-9) is on Pliocene trachybasalts (approximately 2.2- 3.6 Ma). Having said this, alteration to the north of Site C, just to the west of the fault, is on Pleistocene andesites erupted from small cones and craters. This alteration could be contemporaneous with that seen on Mammoth. This paradox is probably only resolvable with age dates on the alteration itself.

Farther to the west in this scene, northeast-trending lineaments other than those mapped as the DFZ were detected, including the feature seen at Site D on Figure 1-9. The zone seen to the west of the letter D is mapped by primarily amorphous silica and lesser kaolinite-alunite. This lineament does not line up directly with any previously mapped DFZ structures, but its trend may be compelling enough to include it in the DFZ. Other individual faults of the DFZ host alteration as mapped by HyMap, however the alteration to the west of the main Discovery fault is a good deal more diffusive, lacking a lot of narrow, distinctive alteration zones. On a broader, regional scale, this may indicate widespread hydrothermal discharge at some undetermined time in the past. The lack of such pervasive alteration to the west of the main Discovery fault appears to indicate that this structure is/was the major zone of upflow in the western caldera, that focused fluids and gasses of the most recent hydrothermal system. Such pervasive and high temperature alteration indicates deep-seated faulting, as Suemnicht and Varga (1988) suggested. If so, it makes sense that this set of faults would not simply end at the northern flank of Mammoth, but continue to the southwest, through Mammoth and into the Sierran block (in line with the northeast trending lineaments mapped on the southwest flank). It is the intersection of these DFZ faults with the Sierran frontal fault that set the stage for the genesis of the domes and flows of the stratovolcano, Mammoth Mt 200,000 years ago.

5.1.3 Hot Creek

Hot Creek is the site of highest hydrothermal flow in the caldera, and as such, hosts fairly high temperature alteration. Fairly widespread amorphous silica lies east of Hot Creek in the Alkali Lakes region, but very little of it appears to be associated with any known faulting, and no coherent linear zones of silica are detected. Most alteration in this scene is actually localized along a 1 km stretch of Hot Creek itself (just to the west of Site A in Figure 1-10). Kaolinite is the most abundant, with lesser amounts of alunite and amorphous silica. The alunite is generally found contained within a halo of kaolinite. The amorphous silica is also found in close association with both minerals at Hot Creek. Some of the mapped alteration coincides with previously mapped faults, however several locations do not show this coincidence. These locations include much of the area downstream of the initial northwest trending fault (to the west of Site A), and an east-west lineament (demarcated by Sites D). The downstream alteration zones along the creek may be due to simple alteration by flow of waters along the creek as it cuts its way down. This Hot Creek flow is approximately 300 ka, so this would allow plenty of time for alteration and downcutting.

Another option entails other structures cutting across the creek. The linear alteration zone delineated by the letter Ds. It was mapped primarily by kaolinite distribution, but both silica and alunite are also detected. Other alteration zones to the south of this one may also be tracks of once vigorous west to east hydrothermal flow (both at Hot Creek and further south at Site C, or to the north at Site E). Such east-west trending structures are rare in the caldera, where most structures are north-south or northwest trending (such as the faults detected at Site B with both kaolinite and alunite). However, the east-west trends are not unprecedented. Bailey mapped a few east-west faults in the caldera, and most recently, Prejean (2001) mapped a set of NNW trending faults in the southern moat of the caldera, using precisely located seismicity. Prejean (2001) suggests the south moat faults are reactivated ring structures, acting as transform faults between the Hartley Springs and Hilton Creek faults. The roughly east-west faults mapped in the HyMap scene of Figure 1-10 may be similar structures. However, they may be too far north to be considered ring fractures. Another possibility invokes the paleotopography of the pre-Long Valley-Mammoth embayment. Perhaps these structures are the vestiges of basement structure that existed before the caldera-forming eruption 760 ka. They have materialized again via regional, favorably orientated, tectonic stress regimes including that from Basin and Range extension and ECSZ shear.

5.1.4 The South Moat

The southern moat has long been a region of interest to volcanologists studying the formation and current state of Long Valley. It is thought to host a shallow magmatic intrusion and to serve as the primary heat source for the Casa Diablo geothermal plant (Vetter and Ryall, 1983; Sorey et al, 1991). The seismicity relocation study of Prejean (2001) indicated that there were well-defined fault planes associated with the seismicity in the southern moat, and that the seismicity was very likely tectonic in origin rather than volcanogenic. Prejean also noted an interesting temporal pattern of seismicity that appeared to establish a link between the upward migration of seismicity and hydrothermal fluid flow. The mapping of high temperature alteration in the same general zone as Prejean's South Moat Fault Zone (SMFZ) is encouraging evidence for surface faulting in this region. To date, no surface expression of the SMFZ was known. The mineral mapping results in Figure 1-12 provides hard evidence for both the existence of the SMFZ, and its theorized role in hydrothermal fluid transport.

Two other east-west structures are mapped via linear alteration distributions in the scene shown in Figure 1-12, however both of these structures have very little associated seismicity. Alteration at Site A in Figure 1-12 is mainly kaosmectite, kaolinite, and amorphous silica, a similar assemblage to that at Site B where Prejean located most of the seismicity. It is likely that Site B is a further continuation of the structure mapped by Prejean (and this study). Most other alteration in the image coincides with previously mapped faults (including the kaolinite-alunite mapped along the Fumarole Valley faults and the Basalt Fumarole fault).

5.2 Hyperspectrally-derived fault and fracture maps: Caldera wide

The results of hyperspectral fault mapping corroborates the existence of most known faulting in the Long Valley region, but they also provide hard evidence for the existence of structural lineaments with little evidence of surface rupture or deformation. Several new lineaments were discussed in Section 5.1, with ancillary evidence proving movement and/or a role in hydrothermal transport are revealed. At the caldera scale, this refined fault mapping has implications for volcanogenesis and tectonics. More regionally, patterns of faulting emerging from this study are evolving into regionally recognizable patterns. The caldera may be a large *local* perturbation, but regionally, it is a minor chunk of crust caught in continent-scale tectonics. As such, the structure seen within the caldera, mimics dominant structure seen regionally within the Eastern California Shear Zone and the Walker Lane.

The main structural trends observed in and around Long Valley Caldera include (1) NNW-SSE, (2) N-S, (3) NE-SW, and (4) WNW-ESE. Surface traces of trends 1 and 2 are dominant, however trends 3 and 4 gain traceable fault area within this study. Figure 1-13 depicts previously known, mapped faults in Long Valley Caldera. The faults in blue are from Bailey (1989) and were compiled from years of field mapping and aerial photo interpretation. Faults in green were taken from Suemnicht and Varga (1988) and represent the collective DFZ as mapped in the field and from air photo. Faults in maroon are from Prejean (2001), and were mapped using precisely located seismicity. At this point, all three sets of faults are accepted as status quo, i.e. they are all assumed to be valid structures with substantial evidence supporting their existence.

Figure 1-14 shows the boundary of the caldera and only those faults and fractures that were mapped using HyMap hyperspectral imagery and that coincide with the previous mapped faults in Figure 1-13. Notice that all the major structural trends were captured with this hyperspectral mapping effort (i.e. the northwest trending resurgent dome faults, the north-south faults in the western caldera, the northeast trending DFZ, the NNW-trending SMFZ and the east moat ring fractures). Some faults are undetected by this method, including most of the faults in the northern one third of the caldera and the majority of the north-south faults in the western caldera. There are several reasons why faults may not be mapped hyperspectrally: not all faults act as conduits for hydrothermal fluid or gas flow; lack of thermal input means no alteration of country rock and soils; alteration is easily erodable, so perhaps alteration in the northern third of the caldera is gone now (the rhyolite flows at those latitudes are ~ 500 ka. Conversely, regions with very recent volcanic activity may not have had time to develop substantial alteration profiles, which may explain the lack of north-south faults detected in the western caldera. Volcanism in this area is generally less than 10,000 years, and the hydrothermal system thought to inhabit the crust in this region peaked only 30,000 years ago (Sorey, 1985). There has been little time for breakdown of minerals by hydrothermal waters. The lack of alteration in some areas may also indicate lack of movement on faults, since movement and deformation on faults keeps fluid pathways open for circulation (and deposition). Lack of measurable surface alteration may indicate faults with little present or paleo movement. On the other hand, the lack of surface alteration does not preclude such faults from having acted as flow conduits in the past (or at present at great depths). Drill core from the LVEW well drilled in the central resurgent dome shows a high degree of hydrothermal alteration, however, there is no alteration on the surface for several hundred meters around the well head. This site was certainly a hydrothermal discharge point in the past, but has ceased this role more recently (Mc Connell et al., 1997). Fault zones seal themselves over long periods of time, so without continued movement to break alteration seals, cycles of fluid flow and subsequent sealing break down.

Figure 1-15 shows all the lineaments mapped that do not coincide with any previously mapped faults (in Figure 1-13). The western caldera has several new northeast trending lineaments, which are most likely related to the DFZ in some way. A few northwest lineaments are mapped in the central caldera, though this trend is subordinate to a general zone of east-west lineaments. Two are fairly substantial (the SMFZ and the Hot Creek Fault that cuts the creek), while most others are smaller sections. It appears to suggest a caldera-scale, east-west structural weakness, the origin of which was discussed in section 5.1.3. A few minor northeast trends are detectable in the central caldera, and several, probably northwest trending ring fractures are mapped in the eastern moat. I consider this interpretation to be the most conservative, although not all of these lineaments have been field checked: about a quarter have been visited, and all were convincing faults or fractures.

Figure 1-16 is an amalgamation of the lineaments shown in Figures 1-14 and 1-15. This figure illustrates an important point regarding remote characterization of active volcanic/geothermal regions. Though all faults were not mapped using hyperspectral imaging, major proportions of them were. A workable structural map of Long Valley caldera can be made solely from the distribution of faults shown exclusively in Figure 1-16. The ring fractures in the western, southern and eastern moats were mapped quite well, as were the major northwest trending resurgent dome faults. The DFZ is clearly mapped with hyperspectral data and thus provides a partial mechanism for localization of magma and hydrothermal discharge in the western caldera. The east-west faults are also easily seen spectroscopically and provide a picture of west to east strain transfer across the caldera, as well as hydrothermal fluid transport. All known major components of Long Valley structure are mapped, as well as several minor components that may prove more important in the future as models evolve.

Figures 1-17 and 1-18 show the final, refined structural map of Long Valley Caldera. Figure 1-17 shows all previously mapped faults in blue with the hyperspectrally-mapped faults in magenta laid on top. It is easy to see in this figure where the new structures are mapped as well as the structures that coincide with previously mapped structures. Figure 1-18 shows a final composite of previously mapped faults and the new structures mapped with hyperspectral data.

Other geothermal regions with similar vegetation and rock types should be easily and efficiently mapped for structural components. Regions with increasing amounts of vegetation will prove to be more difficult, but likely still mappable. Fault and fracture maps such as those shown in Figures 1-17 and 1-18 can be produced in two months or less (including acquisition and pre-processing), which makes the remote characterization and monitoring of remote volcanoes efficient and timely. This final composite allows for several generalizations regarding the usage of hyperspectral imaging for geothermal prospecting and characterization. It also provides new discussion regarding not only the characterization and structural mapping of unknown or poorly studied volcanic regions, but also regarding current structural and tectonic models of Long Valley. Strong support for several recent tectonic models and models of volcanogenesis is presented in the next two sections.

6.0 Implications

6.1 Volcanic and resource characterization via hyperspectral imaging

I wanted to use Long Valley Caldera as a test site to determine what structural, hydrothermal, and geobiological variables can be constrained in a volcanic environment via hyperspectral imagery and minor groundtruth information. Generally, I wanted to resolve how much of a given volcanic region's structure and hydrothermal system can be detected using hyperspectral imaging. Such information can be used as inputs into models for hazard analysis, volcanogenesis studies, and constraining exploration targets in volcanic regions with geothermal potential. Many volcanic regions exist globally with potential both for hazards as well as economic gain via geothermal exploitation. Scores of these regions are poorly characterized due to remoteness and lack of monitoring/assessment funds. This study reveals not only what a hyperspectral survey can expose about an active volcanic environment, but also what it doesn't.

The map of Long Valley structure (Figure 1-16) is an example of the level of detail to expect when using hyperspectral imaging to map faults and fractures in an active volcanic environment. Though only the structures of Figure 12 are corroborated with previous mapping evidence, many of the structures shown in Figure 13 have supporting evidence for their existence too. A qualitative comparison of structural features in Long Valley caldera reproduced with hyperspectral mapping with those known from other approaches indicates that not all structural features are mapped via linear distributions of hydrothermal mineralization assemblages. Quantitatively, only ~ 17% of faults were detected: the total length of mapped faults in the HyMap-imaged area of Long Valley is 420.3 km, which includes mapping by Bailey (1989), Suemnicht and Varga (1988), and Prejean (2001); the total length of hyperspectrally-mapped faults is 72.0 km. While this seems a fairly low number, all the general structural trends are captured in the hyperspectral maps, as well as several newly detected populations Figure 1-15. The 17% relates to total length of faults and fractures, not the proportions of individual faults. A much higher proportion of individual faults was detected, though their entire lengths may not be captured. For instance, of the 3284 meter long secondary structure of the Discovery

Fault Zone, 1306 meters were actually detected in the form of linear distributions of kaolinite and alunite. Although only 39.8 % of the length of the fault was actually mapped, the location and trend of the structure is discernable, and this is most important for the creation of complete structural networks for models, hazard analysis, and geothermal exploration.

We must also consider why certain sets of structures remained undetected in the hyperspectral analysis, and the inherent implications of such omissions for future hyperspectral surveys of other volcanoes. At the simplest level, faults aren't seen because there is no alteration due to lack of fluid or gas flux within these particular structures. This logic suggests that structures without alteration at the surface are either sealed, "scoured", very young, or not actively deforming. Structural conduits that host hydrothermal flow for an extended period of time may eventually self-seal. Presumably, flux did reach the surface within the history of the fault, and thus the lack of surface alteration is still a paradox. Conversely, hydrothermal fluid flux conduits, such as faults, resist sealing by continued deformation. Perhaps the faults without significant alteration are not actively deforming, or are deforming at very slow rates. Removal of altered minerals by glacial scouring is possible in many regions, as is fluvial transport and re-deposition. Most of Long Valley has remained glacier - free since its formation (except the far southwestern section), but fluvial and lacusterine processes have certainly acted on the caldera over the millennia. More recent alteration (associated with the most recent hydrothermal discharge peak at 40Ka) would be relatively immune to these processes however, due to climate changes that reduced the amount of surface water accumulating and flowing through Long Valley. In the same vein, structures that are relatively young may lack a high degree of alteration. This may explain the lack of fault detection in the central/northwestern portion of the caldera around the relatively recent Mono-Inyo volcanic chain. Most of these domes and flows are under 40 ka, several features are only 5 ka, and the Inyo phreatic craters are only ~600 years old. Although the northeast-trending DFZ is quite altered, the north-south trending normal faults that bound many of the volcanic features are almost entirely alteration free, except for a few places on faults near to Mammoth Mt. Such young structures may simply not have had enough time to develop mature circulation patterns leading to substantial alteration profiles. Conversely, the Inyo craters are intensely altered and lie in this north-south fault trend, but the phreatic events that formed these craters likely hosted extreme rates of alteration, comparable to those at hot, actively degassing, volcanoes today. Hot, acidic, steaming vents probably existed in the crater area for hundreds of years cooking the ground and forming the dense alteration distributions we see today on the ground and detect in the hyperspectral imagery. The lack of fault detection in parts of the Long Valley Caldera indicates possible deformation gaps in the north-central portion of the caldera, and extremely young deformation in the western caldera. The lack of alteration-defined faults in the far eastern caldera along the ring fractures and other associated faults is likely due to very little hydrothermal upflow in this region (as most of the waters in the hydrothermal system source from the west and fluxes are much higher in a westerly direction).

The implications for future hyperspectral surveys of poorly known volcanic areas are two-fold. First, linear distributions of hydrothermal alteration minerals can provide workable maps of structural networks in active volcanic regions with a history of hydrothermal discharge. Second, not all structures are mappable using this method, and lack of alteration in a region does not preclude faulting or hydrothermal activity at depth. In addition, although the lack or profusion of alteration in a region hints at relative ages of faulting, hyperspectral imaging analysis per se is incapable of producing actual ages of mineralization. There are some individual spectroscopic phenomena that allow for relative age detection. For example, younger hydrothermally-deposited opal has a different spectral signature from older chalcedonic sinters (due to differences in crystalline structures), and is thus measurable in hyperspectral images. Relative ages of sinter terraces in hot spring areas are theoretically possible, but hard in practice (Kruse, 1998). Density of alteration may indicate prolonged deposition, but spectroscopy cannot confirm this without field data. Finally, hyperspectral imaging at the wavelengths measured in this study does not easily produce lithological maps. Alteration minerals are mapped, while lithologies such as basalt are not. The presence of abundant hematite may indicate a mafic rock, but does not confirm it. Hence, field information is needed to create complete geologic maps.

The success of mapping faults shown in Figure 1-16 suggests that workable structural maps are producible from hyperspectral surveys. In the end, such fault maps provide one piece of evidence for constraining exploration targets for geothermal energy production. It is the combination of structural knowledge with alteration assemblages that provides a complete methodology for hyperspectral-based surveys of potential geothermal areas. Those regions with high faulting and alteration density deserve further attention, both for volcano monitoring and for resource potential. Such surveys done in poorly mapped regions would significantly increase the efficiency of reconnaissance mapping and evaluation in geothermal areas, and would aid in directing field studies to the areas of greatest interest, rather than random, methodical surveying. The fault maps shown in Figure 1-17 and 1-18 also further elucidate how Long Valley is accommodating local and regional stress. Having a complete picture of area structure is very important for modeling of local volcanogenesis and activity, as well as assessing regional tectonic networks. These implications are discussed in the following section.

6.2 Old faults, new volcanoes: strong support for recent models

It is tempting to consider the Long Valley crust as anomalous, due to its recent volcanic activity, and as such, the caldera is generally omitted from regional tectonic models and deformational processes. For example, ECSZ deformation is pervasive in this region of western N. America, however Long Valley Caldera is usually left out of the ECSZ models (with the exception of Trexler (1978) and Bursik and Sieh (1989)). We suggest that, in addition to a good deal of extensional strain, the Long Valley region is accommodating the phase of dextral shear induced by the ECSZ. The hyperspectrally refined fault maps of this study (especially Figure 1-15) reveal structural networks consistent with regional fault patterns, long-term, regional tectonic forcing, and an intimate connection between these structures and volcanogenesis of Long Valley. Hyperspectral mapping provides further hard evidence for models and theories of strain accommodation and volcanogenesis by various groups and individuals (Gilbert et al., 1968; Bailey et al., 1976; Hill et al., 1990; Moos and Zoback, 1993; Suemnicht and Varga, 1988; Prejean, 2001; Smailbegovich, 2002).

Long Valley and the Mono Basin have long volcano-tectonic histories, whose beginnings are rooted in pervasive, mid to late Miocene Basin and Range extensional deformation. The latitudes of proto-Long Valley experienced 1480-2150 m of normal offset on the Sierra Nevada Fault Zone (SNFZ) by around 3 Ma (Unruh, 1991; Huber and Wakabayashi and Sawyer, 2001). A far more staggering figure of 7000 m of normal offset had occurred on the White Mountain Fault Zone (WMFZ) in this time period (Stockli, 1999). It is therefore quite easy to accept that formation and current morphology of Long Valley Caldera is dominantly due to this massive phase of western North American extension. Regionally, the story becomes more complicated. By 6 Ma, inboard migrating, San Andreas-induced, shear deformation had begun to carve the landscape to the south of the Garlock Fault region. This right lateral shear propagated to latitudes just south of Long Valley along the Owens Valley Fault Zone (OVFZ) about 3-1.5 Ma (Stockli, 1999; Henry and Perkins, 2001; Lee et al., 2001). This deformation and its associated structures (dominated by northwest trending, oblique, right-lateral slip normal faults, north trending normal faults, and northeast trending, oblique left-lateral slip faults), are collectively referred to as the ECSZ (Dokka, 1983; Dokka and Travis, 1990a,b; Dokka et al., 1991). The ECSZ eventually empties into the right-lateral shear faults of the Walker Lane further to the northeast in Nevada. This is accomplished by a set of northeast-trending oblique, left-lateral faults located just to the north and east of Long Valley caldera. These transtensional, transfer faults are part of the Excelsior Mountain Fault Zone (EMFZ) as well as the Queen Valley Fault Zone (QVFZ) (Stockli, 1999). These curving transfer faults, their westward extension into the Sierra, and their northeastward transfer of strain, have oft been referred to as the Mina Deflection or Great Structural Knee (Gilbert et al., 1968; Wetterauer, 1977; Stewart, 1988).

The structural networks included in the Bailey (1989) geological map of Long Valley Caldera include the dominant northwest-trending faults seen regionally, but lack the northeast-trending transfer faults seen commonly to the south and north of the caldera. Work by Suemnicht and Varga (1988) resolves this discrepancy with the Discovery Fault Zone (DFZ); a collection of northeast-trending oblique, left-lateral faults in the western caldera that straddle some of the main domes and flows of the Mono-Inyo volcanic chain. Though the existence of these structures was contentious in the past, hyperspectral work in this study provided hard evidence in the form of alunite and kaolinite along mapped sections of the DFZ (see Section 4.2.2 and Figure 1-9). Fieldwork confirmed the identity of this alteration and the presence of a fault plane with lateral slickenlines trending roughly northeast. Furthermore, while high temperature, acid sulfate alteration is ubiquitous east of the main DFZ structure, very little alteration lies to the west (with the exception of the very young alteration associated with the Inyo phreatic craters). This suggests that the DFZ is a main conduit for upward hydrothermal fluid flow, and therefore is likely to be a deep-seated, older structure such as Suemnicht and Varga (1988) suggested. The sparse alteration on the north-south trending faults of the Mono-Inyo volcanic chain suggest deformational youth. It is probable that the highly altered DFZ is much older and taps deeper hydrothermal sources than the younger, north-south faults in the western caldera. The alteration data favor a scenario where north-south faults formed primarily in response to relatively recent, upward magmatic dike propagation in the western caldera (Mastin and Pollard, 1988), while the densely altered faults of the DFZ would be older and reflect long lived stress regimes in contrast to the more recent Basin and Range-assisted extension and volcanism.

However, though older in origin, the DFZ structures are certainly deforming in response to more recent stress regimes. As Ron et al. (2001) point out, structures lacking surface expression and/or seismicity may still reactivate in the face of evolving preferential stress directions. The DFZ are most likely old structures, now reactivating in response to both regional and local extension, as well as possible ECSZ-induced right lateral shear. This strain system leads to left-lateral oblique shear, allowing for transtensional wrenching open of these structures. The intersection of these northeast-trending faults with the young north-south faults likely played a large role in the location of the Mono-Inyo volcanic chain domes and flows, including Mammoth Mt. The extension of the northeast trending DFZ through Mammoth and the southwest flank of the caldera (see Figure 1-7) creates an intersection of northeast (DFZ), north-south, and northwest trending faults beneath the present location of Mammoth, and explains the large volumes of lava in this locale, compared to other spots in the chain.

The upward propagation of deep, northeast-trending Mesozoic basement structures through the caldera crust is not unique. Previously unrecognized east-west trending faults cut through caldera crust in several locales. These structures were mapped using linear distributions of predominately alunite, kaolinite, and amorphous silica (opal) (see Figures 1-10 and 1-12). Though the linear feature mapped in Figure 1-12 roughly coincides with the seismicity of the South Moat Fault Zone (SMFZ) of Prejean (2001), the structures shown in Figure 1-10 (and others mapped and shown in less detail in Figure 1-15) lack associated seismicity and display very little topographic expression. Although the east-west trends match those of ring fractures, they are located quite centrally in the caldera. These east-west trending faults/fractures may be controlled by deep-seated basement structure. Regional, subsurface east-west trends are quite common to the north of Long Valley, and were recently detected in greater detail using magnetic data over the Mono Basin/Aurora-Bodie districts (Phillips et al., 2002). In addition, the projection of the Mammoth Embayment at depth beneath southern Long Valley by Suemnicht and Varga (1988), provides further evidence that a deep, east-west structural weakness may be inherited by the caldera and is propagating upwards through the crust in central Long Valley.

A complex network of obliquely slipping right and left lateral faults is presently deforming the crust at Long Valley latitudes. Oblique shear reached these latitudes no later than 3 Ma and active deformation on transtensional faults to the south began no later than 1.7 Ma (Stockli, 1999; Lee et al., 2001). The initiation of volcanism in the Long Valley/Mono Basin region coincides with this timing (eg. the Glass Mountain volcanics primarily erupted at 1.1 Ma, but leaked for a million years before that) and suggests a volcano-tectonic relationship for Long Valley caldera. Bursik and Sieh (1989) presented evidence for dextral shear north of Long Valley. They suggested further that the Mono Basin is transtensional, formed in response to left-stepping, oblique northwest-trending normal faults and accompanying northeast-trending transfer faults.

To what extent is this shear deformation being accommodated in Long Valley? Geodetic measurements for the area north of the Garlock fault show a total of 13 mm/yr (Miller et al., 2001). Miller et al. suggested that deformation is increasing to the north and west, and that steady northwestward migration of the Sierra Block produces increasing levels of extension to the north. Part of the strain north of the Garlock fault is transferred north and east by sets of northwest, north, and northeast trending transfer faults such as the northwest Hunter Mountain – Saline Valley Fault Zone and northeast Eureka Valley Fault. Miller et al. (2001) measured 7 mm/yr of shear for the Owens Valley Fault Zone (OVFZ), whereas recent, geologically determined, slip rates for the WMFZ at Long Valley latitudes are less than 1 mm/yr (Kirby et al., 2002). Thus, not all ECSZ strain is being transferred to the WMFZ from the OVFZ. Though much strain appears to transfer over to the Fish Lake Valley Fault Zone-Fish Creek Fault Zone, a portion of the 7mm/yr on the OVFZ probably continues north. Low slip rates on the WMFZ imply that some of the OVFZ shear continues north to Long Valley. These geodetic and geologic measurements, in combination with previously noted shear deformation in the Mono Basin north of Long Valley, imply that a portion of Eastern California Shear is being accommodated in the caldera.

Speculations on the role of observed faults for caldera development

How then, would this shear be accommodated in the caldera, and what are the implications? Adding a component of regional dextral shear to regional extension provides further crustal weakening by not only formation of new structures, but by reactivation of older structures that become preferentially oriented to deform in the face of a new strain regime. The northeast-trending DFZ may have begun to act as a transfer zone between the large northwest trending normal and right slip faults, at about 2Ma, where the Hartley Springs Fault acts as the northern fault of the left-stepover, and the Hilton Creek is the southern. The step-over is accomplished by a combination of transtensional faulting in the DFZ and oblique right slip on the WNW-trending structures of the SMFZ. As these transtensional zones evolved, the crust continued to thin and the major structural zones (NW and NE-trending structures esp.) began to act as conduits for enhanced vertical flow of hydrothermal waters, gas, and eventually magma. It is in this same time period, that the Glass Mountain volcanics began their million year span of activity. Bacon (1985) indicates that there is no evidence for the Glass Mountain vents being controlled by regional tectonic stress regimes, however this pile of rhyolites does lie on the northeastern rim of the caldera, in line with the northeast trending DFZ. Perhaps a paleo NE or ENE trend existed in this region and like other similar trends, was reactivated by regional extension and shear, enabling magma migration along a zone of crustal weakness. Any evidence of such a structure would long ago have been buried. As of approximately 1 Ma, the structural integrity of Long Valley crust would have been severely decayed due to normal, shear and transtensional faulting, and subsequent upward magma migration and pooling. The combination of reactivated basement structures (both northeast and east-west trends) and more recent northwest trending structures conspired to create a fault network capable of accommodating complex crustal deformation. The transtensional faulting of the DFZ (and other NE-trending structures) coupled with regional WNW directed crustal extension accommodated by large NW-trending normal faults such as the Hilton Creek Fault, created an environment where long Valley crust (buttressed against the southern Mammoth Embayment boundary), began to extend (and possibly rotate around a vertical axis) more profoundly in the western and central caldera, while the crust in the eastern caldera also extended and enjoyed less impeded southward translation. As Hill has suggested, this creates a levering of the crustal block of Long Valley around the eastern corner of the Mammoth Embayment, allowing for extension and opening of the crust (D. Hill, pers. comm.). All preferentially oriented structures withinin Long Valley would accommodate this regional shear and extensional opening, and would change with time as fault and stress orientations change.

The transtensional opening of various faults all over the caldera allowed for the development of fledgling hydrothermal systems, which broke down and decreased the structural integrity of the crust. This extension and shear also allowed for thinning of the crust, and the upward migration of magma. Levering the Long Valley block around the embayment in a clockwise manner likely reduced lithostatic pressure in the proto-southern moat region, thereby forming the future, primary Long Valley eruption zone (Hildreth and Mahood, 1986). A little over a million years of the above extension, shear, and pervasive hydrothermal alteration created the setting for the massive Long Valley eruption at 760 ka.

7.0 Conclusions

Caldera-wide hydrothermal mineralization maps expose the main structural trends in Long Valley. Though the entire length of intra-caldera faults are generally not detected, sufficient portions of them are mapped for approximations of strike. The age of faulting is not directly discernible, though the overall density of alteration within the deformation zone implies relative ages of fault movement. This appears to be the case in the north-south trending fault systems of the western caldera, where there is very little alteration. Such faults are probably much younger than the highly altered Discovery Zone and Fumarole Valley faults located to the east. Many linear distributions of hydrothermal mineralization are extensive enough, for whole fault trends to be reproducible at the level of detail shown in Bailey (1989); however other regions lack sufficient alteration to map entire fault lengths. In the latter case, without groundtruth or other ancillary information, only the presence of a zone of permeability is suggested. Though likely fault/fracture controlled, the alteration data alone cannot prove this.

Hyperspectrally-mapped faults that coincide with groundbased fault maps such as Bailey (1989) are important because: a) they prove that significant fault and fracture mapping is possible remotely; and b) that the other linear distributions of alteration that don't coincide with previously mapped structures, may in fact be structure themselves. Figure 1-18 is therefore the most complete picture of structure yet produced for the Long Valley Caldera. The importance of this is two-fold. First, the success in reproducing general structural trends in a well-known, well-studied caldera suggests that this technology is usable in its current state for fault and fracture mapping in other poorly known volcanic regions. In some cases, it may also be used successfully in non-volcanic regions, provided there is identifiable mineralization within faults/fractures. Second and more specific to Long Valley, the addition of these refined structural networks to current models of strain accommodation and volcanogenesis in the caldera provides a further level of complexity only hinted at in previous research, i.e. the northeast-trending faults of the western caldera, and the central east-west trending faults that cut through the southern moat and the resurgent dome. In both cases, these faults appear to be older structures that are reactivating in the face of the present day strain regime. They are generally not seismically delineated (with the exception of the SMFZ), but alteration distributions map them unequivocally. High temperature alteration assemblages, such as those measured in the caldera with hyperspectral imaging, must occur along zones of hydrothermal permeability. In general, such zones are coincident with an active fault or fracture. These older fault systems are deep-seated zones that the caldera block inherited through time, post-eruption (Suemnicht and Varga, 1988). The caldera likely owes its existence to these sets of deep-seated structures (Smith and Bailey, 1966), and they also undoubtedly control how the caldera is accommodating present-day strain.